MAGNETOSPHERIC CONSTELLATION: LEVERAGING SPACE 2.0 FOR BIG SCIENCE

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ABSTRACT

Earth's magnetosphere is a large magnetic cavity formed through the interaction of the solar wind and Earth's intrinsic magnetic field. Solar wind energy enters this cavity through a boundary - the magnetopause - separating Earth's field from the solar wind. This energy leads to many forms of ”space weather”, including the aurora, geomagnetic storms, and energization of the Van Allen radiation belts. Despite decades of research, we still do not understand the extent of dayside reconnection sites, nor do we have a quantifiable understanding of how much energy enters the magnetosphere during different solar wind conditions - necessary for space weather prediction. On the nightside, impulsive flows at various spatial and temporal scales occur frequently during storms and substorms, and couple to the ionosphere through still unresolved physical mechanisms. Because the magnetosphere is so large, it has been understood since the dawn of the space age that a full understanding of this complex region could only be achieved with a large fleet of in situ spacecraft. NASA has studied one such constellation, the so-called ”Magnetospheric Constellation” (MagCon), since the 1990's [1], but it is deemed too expensive to implement using traditional approaches. The CubeSat/SmallSat revolution represents a fundamental disruption to traditional mission architectures, and in this paper I will discuss how, by leveraging innovation in spacecraft subystems, advanced manufacturing, and access to space, we can finally realize this long-term vision of exploration and discovery. The proposed modular approach, utilizing rideshare and propulsive ESPAs, would also enable worldwide participation in the mission, and is applicable to any constellation mission, including Earth Science missions.

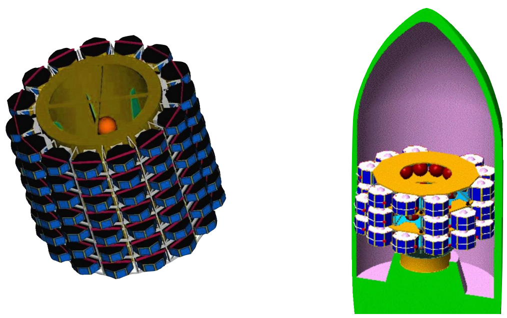
Index Terms— MagCon, Magnetospheric Constellation, Magnetosphere, Space Weather

1. INTRODUCTION

The Magnetospheric Constellation (MagCon) science objective is to determine how the magnetosphere processes, stores, and releases energy derived from the solar wind-magnetosphere interaction. While these processes are fundamental for understanding the magnetosphere as a plasma laboratory, they are also fundamental for understanding and predicting the space weather of the near-Earth environment. Our lack of knowledge regarding the basic processes occurring within the magnetosphere and at the magnetospheric boundary is a major impediment for transitioning basic scientific knowledge of the geospace system into operational use, and hampers our ability to safeguard the human journey into space. MagCon represents a synergy between understanding of basic physical processes and real-world application of this knowledge for the protection of our technology-dependent society. MagCon seeks to understand the magnetospheric system as a whole, by studying not the individual pieces one-at-a-time, but through multipoint measurements across the entire system. With concomitant ground, low-altitude, solar, and solar wind measurements, MagCon would revolutionize our understanding of the magnetospheric response to dynamic solar wind input and the linkages across systems, and hearken in an era of systems science investigations.

An implementation of MagCon was studied in 2014 by United States National Research Council Heliophysics Decadal Survey team [2]. The concept that was studied utilized 36 spacecraft, with low inclination, nested orbits, with perigees near 7-8 RE and apogees dispersed out to 25 RE. Spacecraft were assumed to be 30-kg spinners, with the spin axis perpendicular to the ecliptic, each carrying a boom-mounted magnetometer, a simple electrostatic analyzer, and an energetic particle telescope. While deemed an exciting mission concept, the Decadal Survey concluded that ”[t]o implement such a constellation requires development of small satellite systems and instruments that can be more cheaply manufactured and tested in a reasonable time frame (2-3 years) with acceptable reliability levels, plus a better match between launch vehicle capabilities and constellation mission needs.”

Both the small satellite and launch landscapes have changed significantly since this study, mitigating much of the perceived risk. Since the release of the 2012 Heliophysics Decadal Survey report, the capabilities of small satellites has exponentially increased. With a large and growing SmallSat user community, there are now multiple, low-cost, commercial solutions for radios, propulsion, command and data handling (C&DH), and power systems. Commercial companies have launched constellations of cubesats, and several are planning constellations of 100s or even 1000s of small spacecraft with low per spacecraft production costs. We note that the first iteration of MagCon (Figure 1a) in the mid 1990's had 96 spacecraft; by the early 2000's this had been reduced to 36 (Figure 1b), entirely due to cost constraints. Utilizing the fruits of the Small Satellite revolution, and importantly including new avenues of access to space, a cost-effective MagCon is easily with reach.



(a) 1990's (b) 2000's

Fig. 1. Previous deployment options for MagCon have all involved a dispenser ship, greatly increasing cost and complexity of deployment.

2. MAGCON SCIENCE OBJECTIVES

The MagCon science objective can be broken into two overarching focus areas:

1. mass and energy transfer into the magnetosphere occurring at the magnetospheric boundary; and
2. mass and energy storage, transport and release within the magnetosphere.

The magnetopause boundary, both at the dayside and flanks, is the site where solar wind flow energy is transferred into the magnetosphere. Magnetic reconnection is believed to be the dominant mechanism of energy transfer during southward IMF, yet we do not know the temporal or spatial scales of reconnection. Other coupling mechanisms, including the Kelvin-Helmholtz instability and diffusion induced by wave-particle interactions, provide additional mass and energy transport across the magnetopause boundary. In addition to fundamental questions regarding the interaction, we still do not have a quantitative understanding of energy transfer into the magnetosphere. The best coupling functions are able to account for only 70-80% of the observed energy input, suggesting major gaps in our understanding of the coupling. Substantial questions regarding the input and transfer of energy into the magnetosphere remain, and single point or narrow clusters of observations remain inadequate to the task of understanding when, where, and under what conditions the different modes of energy input occur. Only MagCon offers the ability to finally understand the critical pathways of energy input.

Meanwhile, the magnetotail is a critical volume of geospace for energy storage and releases, where global circulation of magnetic fields and plasmas is regulated in response to changing solar wind conditions. In it, impulsive, localized flow bursts launch and dissipate, powerful electrical currents form and evolve abruptly, and magnetic energy is explosively converted to particle energy. The scale, dynamism, and evolution of the magnetotail have evaded our efforts to observe and understand it using individual spacecraft. Fundamental questions concerning the dynamic response of the magnetotail remain unanswerable with the current observatories.

Magnetospheric Constellation is the logical outgrowth of a sequence of Explorer and STP missions designed to explore plasma transport and energy conversion processes over spatial sizes ranging from the distance to the Sun to the size of low energy particle gyro-orbits. The Magnetospheric Multiscale (MMS) mission will focus on the smallest scale, targeting the microphysical processes of magnetic reconnection. The THEMIS mission targeted a one-dimensional view of the magnetotail, a substantial advancement over the study of complex phenomena using individual spacecraft. Yet this one-dimensional mission was designed to answer a narrowly defined question of which of the two substorm models was acting. MagCon will establish a 2-D array of spacecraft both along and across the magnetopause boundary and the magnetotail, designed to produce for the first time a truly complete understanding of mass and energy transport. Ultimately, it will yield a new foundation on which we shall build a predictive science of next generation magnetospheric meteorology and forecast models, adding to our collective body of knowledge relating to fundamental physics of space weather behavior. It directly addresses LWS program goal #8, Dynamic Geospace Coupling, while also providing the often required but currently missing global magnetospheric context for ionospheric, thermospheric and inner magnetospheric missions.

3. TECHNICAL IMPLEMENTATION

3.1. Spacecraft Bus

Enabling technologies for MagCon have been developed and flight validated for the ST-5 mission that was developed at NASA GSFC as part of the New Millennium Program. ST-5 was a small (25 kg), spin-stabilized spacecraft capable of science investigations from LEO out to beyond geosynchronous orbit. The bus has sufficient mass and power resources to support typical magnetospheric instrumentation such as electrostatic analyzers, solid-state detectors, electric field investigations, and magnetometers. Figure 1b shows the implementation of MagCon described in the last STDT report (ref), and one can see that the spacecraft was baselined as ST-5 copies. Since the launch of that mission in 2006, subystem technology has advanced considerably, and it is necessary to update the avionics with newer components. Yet, the mechanical structure of ST-5 is a good baseline, and we keep that structure in the implementation designed here.

An updated ST-5 bus has been scoped for MagCon. Additional batteries are included for power during eclipses of up to 2.5h, and some additional shielding has been added for radiation tolerance. Four additional cold-gas microthrusters are included to assist with orbit, attitude and spin control. Pressurizing the original cold gas tank to full pressure increases the onboard delta-V capability for each probe to 17 m/s, which we believe to be sufficient for the limited orbital maneuvers required for the mission (primarily orbit maintenance due to lunar perturbations). Cold-gas systems are ideal for a multi-spacecraft build of this type, since they are simple, safe, inexpensive, and do not require special handling, thereby keeping costs down. Other high Isp SmallSat propulsion systems are now becoming available, and would greatly increase the ΔV available. COTS solutions exist for other subsystems, including C&DH, EPS, and communication. We find that existing commercial bus subsystem technology is sufficient for this mission, and do not find any need for new technology development.

Table 1. Current best estimate mass, power and recurring cost for a MagCon spacecraft.

	Mass (kg)	Power (W)	Cost ($k)
C&DH	2.8	5.0	400
Power	5.2	1.1	300
Comm	3.5	3.6	500
Propulsion	2.3	0.2	800
Mechanical	10.0	0.0	1000
ACS	0.4	0.3	500
Thermal	0.8	0.7	130
Harness	3.5	0.03	-
Instruments	6.3	4.5	2000
I&T			350
Totals	34.8	11.83	5980

To carry out the science investigations outlined in Section 2, the MagCon probes will require a magnetometer and electrostatic analyzer to achieve the minimum science objectives. The addition of a small solid-state telescope would add little cost but would enhance the science return greatly (particularly for an inner magnetosphere petal). ST-5 carried a miniature fluxgate magnetometer mounted atop a small boom. Neither the magnetometer nor the boom require any re-engineering for MagCon, and could be used as designed. The addition of both an electrostatic analyzer and solid state telescope of the size and mass of the THEMIS ESA and SST, for example, is easily accommodated. Table 1 summarizes the current best estimate (CBE) for mass, power usage, and cost for the MagCon bus.

Our current best estimate for the first copy of a MagCon bus is $20M. Table 1 shows the #2-N per copy cost, which we estimate is $\sim$ 6M. A full spaceflight mission requires further expenditures, such as program management, safety and mission assurance, etc. Racking up these costs we have:

Table 2. Costs for a full mission incorporating 12 spacecraft, including reserves, show a total cost of $225M. Costs are broken down into a traditional Work Breakdown Structure (WBS).

WBS	cost
1-3. Management, SMA, SE	$25M
4. Science	$10M
5-6. First copy	$20M
5-6. #2-12 copy ($6M)	$66M
7. Mission operations	$15M
8. pESPA	$25M
9. Ground system	$6M
10. I&T (to pESPA)	$6M
Total	$173M
Reserves (30%)	$52M
Total	$225M

For 12 spacecraft, we have a total mission cost of $225M, including launch and operations, a tremendous decrease from previous designs. As we describe below, a large cost savings is achieved by rethinking launch and constellation formation.

3.2. Carrier, Launch, and Deployment

Previous approaches to MagCon launch and constellation formation, including the one studied by the 2012 Heliophysics Decadal Survey, relied on a single, dedicated launch vehicle, and a dispenser ship, as shown in Figure 1 [3, 4]. The dispenser ship would carry onboard propulsion and power generation capability sufficient to alter the apogees from the injection orbit out to ~ 25 RE. Because of the critical importance of the dispenser ship and the necessary capabilities, the cost of such a dispenser ship could easily exceed several $100M. The cost of a single EELV is also >$150M. Together, the mission could easily expend $400M before the spacecraft are even built.

We offer an alternative approach to launch and constellation deployment. Rather than a unique dispenser ship, we utilize commercially available propulsive ESPAs (pESPA). And rather than a dedicated launch vehicle, we take advantage of excess launch capacity and stack the propulsive ESPA below the primary spacecraft and rideshare to a temporary orbit. Geosynchronous transfer orbit is sufficient; super-synchronous transfer orbit would be even better. With this approach, we eliminate the full launch vehicle cost in favor of a modest rideshare cost, and replace the unique dispenser ship with a low-cost propulsive EPSA.

Figure 2 shows such an ESPA configuration. Each of 6 ports contains 2 ST-5 sized spacecraft; the carrier therefore contains 12 spacecraft. A notional deployment scheme is as follows. A Falcon-9 or equivalent launch vehicle delivers the primary to a GTO or super synchronous orbit. The launch vehicle then deploys the pESPA, and the pESPA performs a burn to raise perigee to 6-8 RE, then another to raise apogee to the desired orbit. Once the final science orbit is established, each of the 12 individual MagCon spinners are deployed, with no specific orientation required. Each spacecraft carries sufficient onboard delta-V to reorient so that the spin axis is nominally perpendicular to the ecliptic, spin up or down as required, and impart delta-V as necessary to move ahead of or behind its neighbor, as necessary to achieve the required orbit separations.

We note that this modular approach would enable contributions from partners worldwide. Space agencies, such as NASA, JAXA, and ESA, could each provide a fully integrated set of 12 spacecraft at relatively low cost. Additional partners could provide single spacecraft to be integrated to the pESPA. The modularity and flexibility afforded by rideshare and propulsive ESPAs is applicable to any constellation, particularly constellations requiring different orbit planes, such as Earth Science applications.

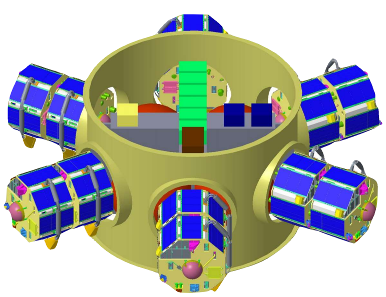


Fig. 2. The proposed deployment plan, utilizing the use of propulsive ESPAs, is highly modular, cost-effective, and enables worldwide participation.

3.3. Data Collection and Communication

Data collection from a constellation of up to 36 spacecraft will require some degree of automation in order to keep Phase E costs reasonable. Decreasing the number of personnel required to manage 36 probes is essential for maintaining a cost-effective mission. In the latter half of the mission ST-5 successfully demonstrated a "lights-out" phase of mission operations, whereby the rapidly configurable architecture of the Goddard Mission Services Evolution Center (GMSEC) was allowed to operate the constellation and downlink data without intervention by ground personnel. The success of the ST-5 "lights-out" operations demonstrates a path forward for reducing cost and complexity for mission operations, and we suggest a similar mission operations and downlink paradigm for MagCon.

4. SUMMARY

We have provided a low-cost, easily implemented, mission designed to determine how mass and energy flow through the boundaries of and within geospace. Magnetospheric constellations have been a long-acknowledged requirement for true understanding of the magnetosphere, appearing consistently in previous NASA Roadmaps. Yet to this point technical and cost concerns have postponed development of this mission. The fundamental science objectives of MagCon remain unsolved, and cannot be solved using single spacecraft or groups of tightly clustered spacecraft. With the success of ST-5, THEMIS, and other small satellite platforms, including CubeSats, the technical and cost obstacles have been overcome. The proposed modular approach, utilizing rideshare and propulsive ESPAs, would also enable worldwide participation in the mission, and is applicable to any constellation mission, including Earth Science missions. In short, we find there are no technological hurdles to this compelling science mission.

5. REFERENCES

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